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A DETERMINATION OF THE 0° ELASTIC

MODULI AND COMPRESSIVE ALLOWABLE

STRENGTH FOR 2-PLY, $0-90^\circ$ GRAPHITE

EPOXY LAMINATE

Douglas M. Hoon
Course II
May 1976

A DETERMINATION OF THE 0° ELASTIC MODULI AND COMPRESSIVE ALLOWABLE STRENGTH FOR 2-PLY, 0-90° GRAPHITE/EPOXY LAMINATE.

by

DOUGLAS M. HOON

B.S., United States Military Academy
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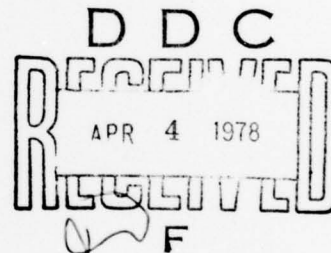at the

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A DETERMINATION OF THE 0° ELASTIC MODULI AND COMPRESSIVE

ALLOWABLE STRENGTH FOR 2-PLY, 0-90° GRAPHITE/EPOXY LAMINATE

by

DOUGLAS M. HOON

Submitted to the Department of Mechanical Engineering
on 1 May, 1976 in partial fulfillment of the requirements
for the Degree of Master of Science.

ABSTRACT

Little data is currently available concerning the properties
of thin graphite/epoxy laminates supported by low density foam
cores. To help fill this information gap a testing program has
been initiated at Massachusetts Institute of Technology. The
testing method, including preparation of test specimens, is
outlined and the results of the first tests of 0-90° laminates
are presented. Analysis of the test results is limited to
calculation of the Normal Distribution parameters for the 0°
elastic moduli and the Weibull Distribution parameters for the
0° compressive strength. Methods of failure are documented
with photographs and explanatory text.

Thesis Supervisor: James W. Mar, Sc.D.
            Title: Professor of Aeronautics and Astronautics

ZERO TO 90 DEGREE

ZERO DEGREE

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Introduction

The potential of the advanced composites have been widely recognized in recent years and a great deal of information has been accumulated by various manufacturers and users. Most of this data, however, describes the properties which can be expected in relatively thick laminates (10-100 plies) after the recommended curing cycle. (See Appendix A.) The properties which can be expected in lightly loaded structures using thin laminates (1-3 plies) cured at atmospheric pressure and supported by low density (3-6 pcf) foam cores are less well known.

In an attempt to fill this information gap several people at Massachusetts Institute of Technology have become involved in a program of testing single graphite fibers and composite beams with thin graphite facings and foam cores. The work that follows represents the first step in that program for testing composite beams with 2-ply 0°-90° orientation facings and is believed to be the first study of its kind conducted anywhere. Twenty beams were tested using two types of foam cores with the intent of determining compressive allowable strengths and elastic moduli of the laminates in the longitudinal direction.

Description of Composite Beams

A composite beam as discussed in the following work is a beam

constructed with graphite facings and a foam core. (See Figure 1.)
The graphite facings provide the tension and compression strength
of the beam as well as providing the beam resisting moment. The pur-
pose of the foam is to separate the graphite facings, give continuous
support to prevent buckling, and to resist shear forces. To prevent
local failure at the loading points mahogany end blocks were substi-
tuted for the core material.
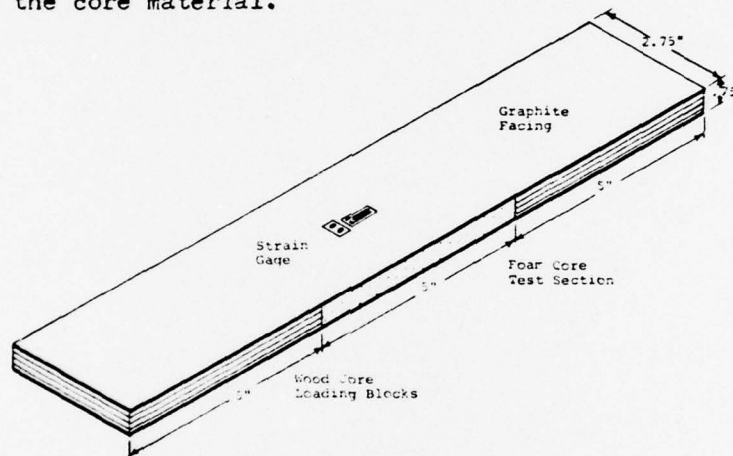
Figure 1
Typical Composite Beam

The graphite material was manufactured by Hercules Incorporated
in 12" pre-preg tapes. The various mechanical and physical properties
of the tape are listed in Appendix A. The foam used in the first
eight beams was Upjohn's CPR Urethane Foam. That used in the last 12
beams was Airex Polyvinyl Chloride Foam. Foam properties are also
listed in Appendix A.

Preparation of Beams

The fabrication of each composite beam consisted of three distinct steps. These were: (1) curing and sizing of the graphite laminate; (2) preparation of the core; and (3) the secondary bonding of core and facing.

The preparation of the graphite facing was the most difficult as well as the most important step in the construction process. The temperature during cure appeared to make some difference in final properties and the measure of vacuum was important in determining the quality of interlaminar bonding as well as laminate thickness and weight. The layup procedure involved placing the pre-preg tape between blotting layers (fiberglass cloth) and release material (peel-ply cloth) and mounting the several layers upon a steel plate to prevent crushing or distortion during cure. (See Figure 2.) The

1--Teflon coated steel plate
2--Bottom fiberglass layer
3--Bottom peel-ply layer
4--16" x 12" laminate of 1-0° ply
    and 1-90° ply
5--Top peel-ply layer
6--Top fiberglass layer
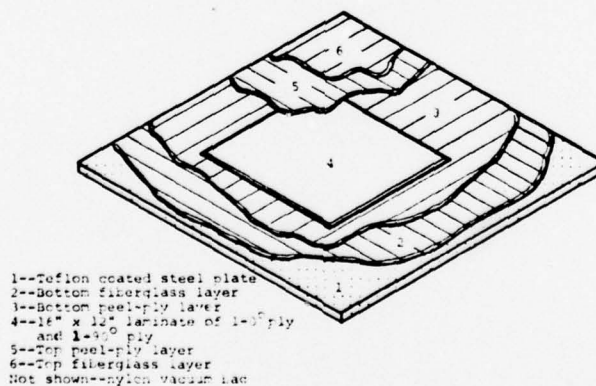Not shown--nylon vacuum bag

FIGURE 2
Graphite Curing Layup

entire layup was then sealed inside a nylon vacuum bag, evacuated, and cured for $2\frac{1}{2}$ hours at a temperature of $350^{\circ}F$.* At the end of its curing cycle the large sheet of laminate was cut to proper size on a sheet-metal shear.

The preparation of the core was much easier. The wood and foam blocks were cut to size on a table saw and glued together in a special jig. The core was then put on a milling machine to produce flat, parallel facing surfaces. Light sanding to remove any roughness or fuzziness was the last step in core production.

Secondary bonding was necessary because the foam cores could not withstand the high temperatures used to cure the graphite. Bonding was done using Smooth-On EA-40 epoxy under vacuum pressure at room temperature. The vacuum bag layup was similar to the graphite curing layup described above. After the epoxy had cured the beams were resized to adjust for any slippage of the graphite during cure.** Excess epoxy was sanded from the edges on a belt sander and from the surfaces to be instrumented with #220 wet or dry sandpaper.

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* Various other temperature cycles were tried early in the program in an attempt to reduce the laminate thickness toward the nominal value of .0052" per ply obtained by the manufacturer during high pressure curing. For the various temperature cycles tried see Table 1.

** The graphite facings frequently slipped sideways such that part of the graphite would be unsupported while a corresponding portion of the core would be bare. Resizing was done on a power sander to adjust beam width such that uncovered core areas were removed.

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Testing Procedure

The beams were instrumented with Micro Measurement EA-13-182BB-120 Strain Gages. Gages were placed on both faces in the 0° orientation and were placed at the center of the beam facings to reduce any edge or end effects. No attempt was made to measure the transverse strain.

The beams were tested for their tension and compression moduli and their compressive failure strength using four-point loading. A Baldwin-Emery SR4 Model FGT test machine was used for loading. A BLH Type 20 strain indicator was used to measure strains on the first eight beams. A BLH Model 1200 strain indicator was used to measure strains on the last twelve. Loading steps of 20-50 pounds were used so that observations of the beam and several measurements could be recorded throughout the loading cycle.

Analysis of Data

The loading geometry was such that the moment in the test section was 1.38 times the load applied by the testing machine. The beam moment of inertia was determined as for a rectangular cross-section using average facing and core thicknesses at the

strain gage centerline and ignoring the contribution to bending
stiffness of the foam. Stresses were then computed using the
familiar relationship S=My/I. Tension and compression moduli
were determined by calculating the slope of the linear portion
of the stress-strain diagrams. Calculation of the Weibull para- -
meters for compressive failure strength was done with the help
of a computer program previously developed in the Department of
Aeronautics and Astronautics. The geometry of the loading
mechanism is shown in Figure 3.

Figure 3
Beam Loading Geometry

Findings

In light of these tests it appears that the Polyvinyl Chloride
Foam may offer core properties which will satisfy the requirements

of lightly loaded composite structures. It is easy to work with
and allows the laminate to develop good compressive strength
without buckling. The Urethane Foam, however, does not seem to
be a satisfactory core material. In all cases where urethane was
used beam failure was due to a tension failure of the foam which
allowed the graphite to buckle outward at relatively low beam
loading. Photographs of the various modes of failure are presented
in Appendix B.

With PVC foam cores the laminate demonstrated mean elastic
moduli of 7.38 MSI in compression and 7.59 MSI in tension. The
compressive allowable strength was calculated to be 272 pounds per
inch. Modes of failure were an apparent compressive failure of
the graphite and a combination compression failure of both the
foam and the graphite simultaneously.

The testing methods used appear, in retrospect, to be sound
and should be continued as such. Future testing may well yield
higher moduli and allowable strength as additional experience is
gained and if more attempt is made to closely follow the recommended
curing temperature cycle published by the manufacturer.

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EXPERIMENTAL

DATA

Beam #	Core properties Width (in)	Thickness (in)	Length (in)	Material	Average facing thickness (in)	N max (lb/in)	Tension modulus (10^6 psi)	Compression modulus (10^6 psi)	Failure mode	Curing Cycle
1	2.62	.767	5.1	U	.0132	234	7.41	7.04	a	Unknown
2	2.65	.771	5.1	U	.0135	170	6.60	5.72	a	Unknown
3	2.62	.765	5.1	U	.0129	221	7.63	6.83	a	Unknown
4	2.65	.772	5.1	U	.0172	334	6.37	8.00	a	a
5	2.59	.766	5.1	U	.0142	223	6.92	7.22	a	b
6	2.65	.779	5.1	U	.0148	279	7.41	7.58	a	b
7	2.69	.781	5.1	U	.0176	293	6.08	7.63	a	c
8	2.62	.764	5.1	U	.0185	327	6.15	6.15	a	c
9	2.47	.721	5.0	PVC	.0153	642	7.33	7.33	b	d
10	2.66	.693	5.0	PVC	.0153	554	7.17	6.78	b	d
11	2.49	.682	5.0	PVC	.0143	507	7.63	7.66	b	e
12	2.40	.730	5.0	PVC	.0145	456	7.14	7.35	c	e
13	2.65	.692	5.0	PVC	.0143	469	8.16	7.55	b	e
14	2.65	.715	5.0	PVC	.0144	461	7.60	7.60	b	e
15	2.64	.710	5.0	PVC	.0138	366	7.66	7.37	c	e
16	2.64	.669	5.0	PVC	.0140	517	7.78	8.10	c	e
17	2.68	.714	5.0	PVC	.0145	513	7.56	7.22	c	e
18	2.49	.705	5.0	PVC	.0138	510	7.53	7.14	d	e
19	2.57	.704	5.0	PVC	.0136	419	7.63	7.49	c	e
20	2.57	.705	5.0	PVC	.0142	520	7.91	6.94	c	e

Notes:

Material--U designates Upjohn's 9006-4 Urethane; PVC designates Airex Polyvinyl Chloride.

Failure mode--"a" is tension failure of the foam; "b" is compression failure of the graphite facing; "c" is combination failure of both foam and graphite in compression; "d" is compression failure of graphite originating at site of earlier ply delamination.

Curing Cycles--"a" is 2.75 hrs @ 350°F; "b" is 3 hrs @ 250° and 1 hr @ 350°; "c" is 3 hrs @225°, 1 hr @ 350°; "d" is 2.5 hrs @225°, 1.75 hr @ 350°; "e" is 2.5 hrs. @ 350°F.

TABLE 1

TABLE 2   STATISTACAL DATA

Beams	Normal Distribution Parameters for Elastic Moduli (MSI)				Weibull Parameters for Compressive Strength		
	μ_{E_c}	σ_{E_c}	μ_{E_t}	σ_{E_t}	$\hat{\alpha}_N$	$\hat{\beta}_N$	f_B
1-8	7.02	.77	6.82	.61	5.62	282.0	.35
9-20	7.38	.35	7.59	.29	7.66	523.7	.52

Note: N_B, the design allowable compressive load per inch, is calculated from the above as $N_B = f_B \times \beta_N$ and represents that value of N such that 90% of all samples (future) will fail at some load greater than or equal to N_B with 95% confidence.

COMPRESSIVE ALLOWABLE STRENGTH WITH URETHANE FOAM CORE: 98 lb/in.

COMPRESSIVE ALLOWABLE STRENGTH WITH PVC FOAM CORE: 272 lb/in.

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$E_t = 7.41$ MSI

$E_c = 7.04$ MSI

+ Compression
• Tension

SPECIMEN NUMBER: 1-MOON BEAM #1

DATE OF TEST : 15 DEC 75

CORE MATERIAL : CPR URETHANE 9306-3

CORE DIMENSIONS: 0.767 X 2.620 X 5.100 INCHES

PLY THICKNESS : 0.0132 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN TENSION (U-IN/IN)	STRAIN COMPRESSION (U-IN/IN)
6.	307.	0.	0.
26.	1330.	161.	162.
46.	2352.	286.	276.
66.	3375.	416.	412.
86.	4399.	589.	552.
106.	5421.	699.	696.
126.	6444.	841.	852.
146.	7466.	973.	997.
166.	8489.	1136.	1138.
188.	9618.	1252.	1304.
206.	10575.	1361.	1431.
225.	11506.	1499.	1588.
246.	12580.	1637.	1765.
266.	13603.	1760.	1919.
285.	14575.	1892.	2089.
306.	15649.	2075.	2261.
326.	16671.	2218.	2533.
346.	17694.		

MAXIMUM LOAD = 346. POUNDS

MAXIMUM STRESS = 17694. PSI

MAXIMUM W = 239. LB/IN

16

SPFCIMEN NUMBER: 1-BOON BEAM #2

DATE OF TEST   : 15 DEC 75

CORE MATERIAL   : GPB URETHANE 2216-4

CORE DIMENSIONS: 0.771 X 2.651 X 5.100 INCHES

PLY THICKNESS   : 0.0135 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN TENSION (U-IN/IN)	STRAIN COMPRESSION (U-IN/IN)
6.	295.	0.	0.
27.	1331.	135.	134.
42.	2065.	302.	315.
66.	3245.	465.	520.
86.	4223.	505.	665.
106.	5292.	766.	863.
126.	6195.	915.	1042.
149.	7277.	1063.	1224.
166.	8162.	1105.	1389.
186.	9145.	1363.	1563.
206.	10129.	1525.	1765.
226.	11112.	1669.	1940.
246.	12095.	1810.	2150.
256.	12587.		

MAXIMUM LOAD = 256. POUNDS

MAXIMUM STRESS = 12587. PSI

MAXIMUM M =   170. IN/IN

SPECIMEN NUMBER: 1-HCOM BEAM #3

DATE OF TEST   : 17 DEC 75

CORE MATERIAL : CPR URETHANE 9006-4

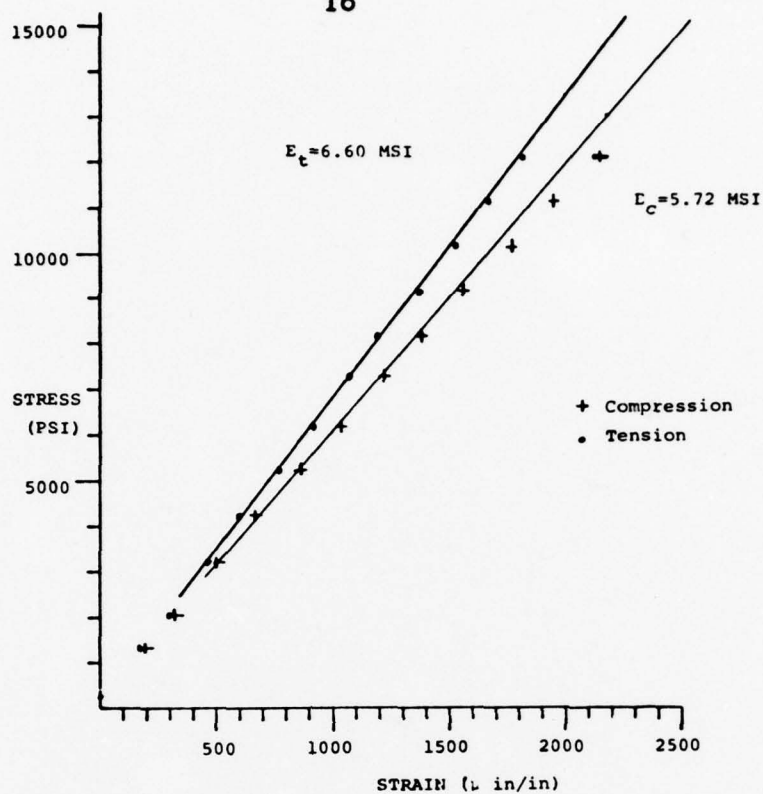CORE DIMENSIONS: 0.765 X 2.622 X 5.100 INCHES

PLY THICKNESS : 0.0120 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN TENSION (U-IN/IN)	STRAIN COMPRESSION (U-IN/IN)
6.	315.	0.	0.
30.	1575.	285.	270.
50.	2598.	371.	409.
66.	3464.	493.	541.
88.	4409.	627.	678.
105.	5562.	769.	862.
126.	6613.	895.	1003.
146.	7663.	1042.	1169.
166.	8712.	1172.	1310.
185.	9720.	1314.	1455.
206.	10812.	1441.	1596.
226.	11861.	1583.	1743.
244.	12806.	1724.	1873.
266.	13961.	1861.	1995.
285.	14958.	1994.	2022.
315.	16538.	2135.	2155.
326.	17110.	*****************************	

MAXIMUM LOAD = 325. POUNDS

MAXIMUM STRESS = 17110. PSI

MAXIMUM N =   221. LB/IN

18

E_c=8.00 MSI

E_t=6.37 MSI

+ Compression

• Tension

STRESS
(PSI)

15000

10000

5000

500   1000   1500   2000   2500   3000

STRAIN (μ in/in)

SPECIMEN NUMBER: 1-HC2N SPAN #0

DATE OF TEST   : 15 DEC 75

CORE MATERIAL : CRB URETHANE 2006-4

CORE DIMENSIONS: 0.772 X 2.652 X 5.120 INCHES
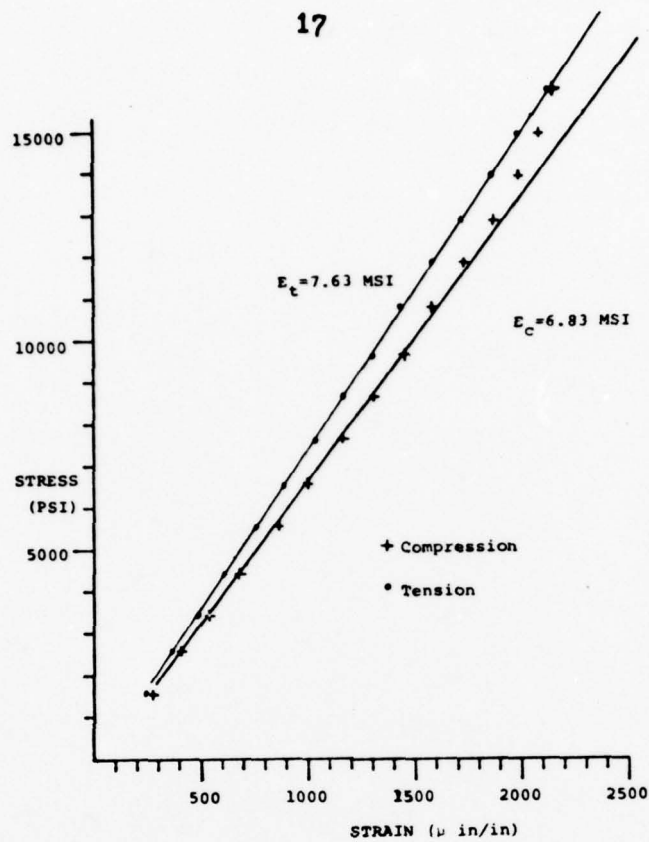
PLY THICKNESS : 0.0172 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN TENSION (μ-IN/IN)	STRAIN COMPRESSION (μ-IN/IN)
6.	232.	0.	0.
27.	1016.	152.	216.
47.	1823.	272.	316.
69.	2627.	393.	314.
95.	3260.	426.	399.
106.	4065.	635.	496.
126.	4833.	765.	603.
146.	5560.	899.	635.
165.	6367.	999.	748.
186.	7113.	1127.	889.
207.	7903.	1249.	993.
226.	8669.	1364.	1077.
246.	9036.	1497.	1160.
269.	10219.	1624.	1262.
285.	10932.	1773.	1332.
306.	11737.	1901.	1411.
326.	12305.	1977.	1513.
346.	13372.	2095.	1599.
367.	14077.	2213.	1676.
386.	14876.	2330.	1779.
406.	15623.	2432.	1792.
426.	16395.	2556.	1929.
446.	17103.	2667.	1945.
446.	17475.	2776.	1919.
486.	18642.	2917.	1792.
506.	19433.		

MAXIMUM LOAD = 506. POUNDS

MAXIMUM STRESS = 19433. PSI

MAXIMUM N = 338. IN/IN

$E_c = 7.22$ MSI

$E_t = 6.92$ MSI

STRESS (PSI)

+ Compression
• Tension

STRAIN (μ in/in)

SPECIMEN NUMBER: 1-HOOP BEAM #5

DATE OF TEST : 15 DEC 75

CORE MATERIAL : C22 URETHANE 0106-4
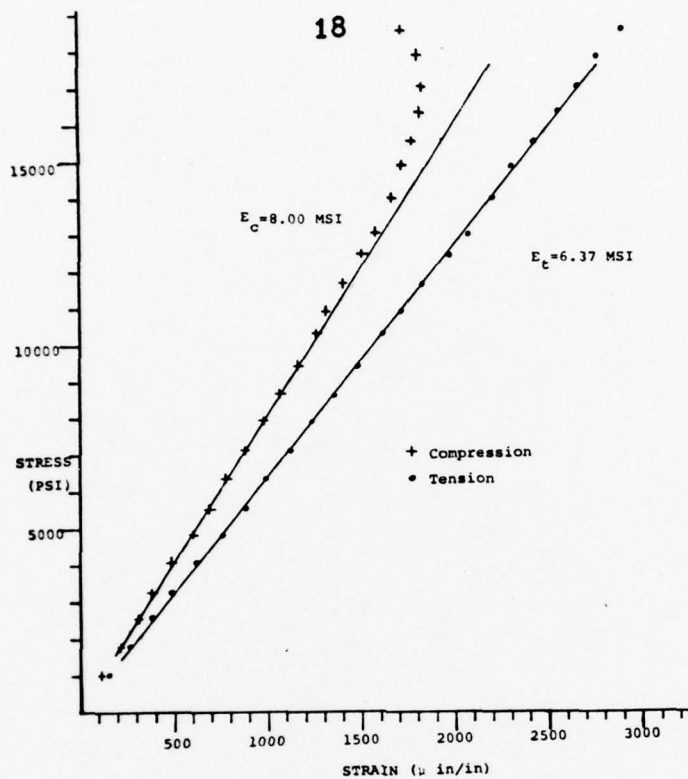
CORE DIMENSIONS: 0.766 X 2.500 X 5.100 INCHES

PLY THICKNESS : 0.0142 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN TENSION (U-IN/IN)	STRAIN COMPRESSION (U-IN/IN)
6.	339.	0.	0.
27.	1338.	205.	199.
46.	2212.	311.	297.
66.	3174.	442.	417.
84.	4039.	592.	533.
116.	5037.	755.	722.
126.	6059.	886.	821.
146.	7021.	1042.	991.
167.	8031.	1167.	1101.
186.	9044.	1311.	1246.
206.	9976.	1439.	1391.
226.	10868.	1567.	1526.
246.	11835.	1737.	1692.
265.	12742.	1943.	1846.
286.	13753.	1171.	2106.
307.	14761.	2135.	2235.
326.	15677.		

MAXIMUM LOAD = 326. POUNDS

MAXIMUM STRESS = 15677. PSI

MAXIMUM M = 233. IN/IN

20

$E_c = 7.58$ MSI

$E_t = 7.41$ MSI

+ Compression

• Tension

STRESS (PSI)

STRAIN (µ in/in)

SPECIMEN NUMBER: 1-HOOK BEAM #6

DATE OF TEST   : 17 DEC 75

CORE MATERIAL : C2P URETHANE 9306-4
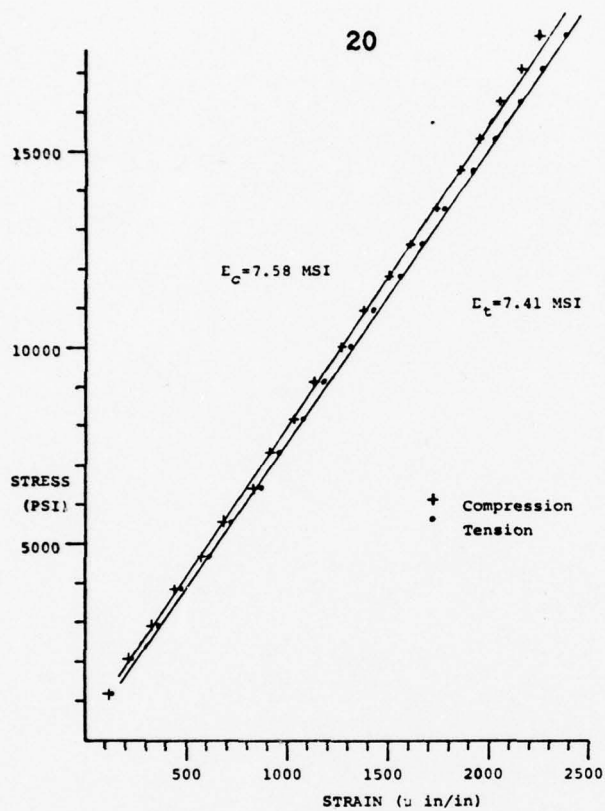
CORE DIMENSIONS: 3.779 X 2.650 X 5.100 INCHES

PLY THICKNESS : 0.0149 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN TENSION (U-IN/IN)	STRAIN COMPRESSION (U-IN/IN)
6.	266.	0.	0.
28.	1341.	141.	132.
47.	2293.	283.	274.
66.	2925.	362.	333.
96.	3912.	478.	447.
106.	4619.	609.	575.
126.	5595.	723.	685.
146.	6471.	879.	807.
166.	7357.	959.	917.
185.	8199.	1031.	1032.
206.	9112.	1131.	1146.
226.	10017.	1313.	1269.
247.	10947.	1447.	1397.
266.	11730.	1559.	1504.
286.	12676.	1672.	1611.
305.	13519.	1789.	1724.
327.	14411.	1926.	1851.
346.	15335.	2007.	1959.
367.	16366.	2163.	2064.
386.	17153.	2233.	2165.
406.	17795.	2333.	2252.
426.	18891.		

MAXIMUM LOAD = 426. POUNDS

MAXIMUM STRESS = 18891. PSI

MAXIMUM E =   270. IN/IN

21

STRESS
(PSI)

15000

10000

5000

E_c=7.63 MSI

E_t=6.08 MSI

+ Compression
• Tension

500   1000   1500   2000   2500

STRAIN (μ in/in)

SPECIMEN NUMBER: 1-4CON BEAM #7

DATE OF TEST   : 16 DEC 75

CORE MATERIAL   : CPR URETHANE 9006-2

CORE DIMENSIONS: 0.781 X 2.690 X 5.122 INCHES
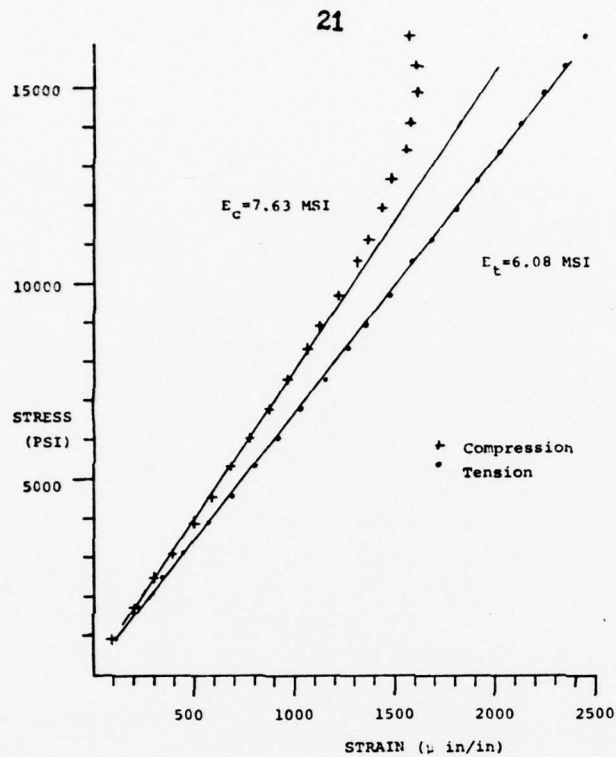
PLY THICKNESS   : 0.0176 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN TENSION (U-IN/IN)	STRAIN COMPRESSION (U-IN/IN)
6.	210.	0.	0.
26.	949.	111.	95.
43.	1752.	225.	203.
69.	2519.	307.	322.
97.	3175.	457.	396.
106.	3869.	573.	502.
126.	4509.	693.	595.
145.	5228.	834.	691.
166.	6050.	915.	795.
196.	6794.	1025.	875.
206.	7511.	1154.	967.
229.	9321.	1263.	1060.
244.	9354.	1359.	1136.
266.	9737.	1482.	1220.
289.	10510.	1535.	1311.
306.	11167.	1692.	1362.
325.	11837.	1817.	1443.
346.	12627.	1922.	1507.
367.	13323.	2023.	1550.
386.	14037.	2143.	1519.
407.	14453.	2256.	1615.
423.	15546.	2351.	1623.
447.	16313.	2456.	1590.
456.	16531.		

MAXIMUM LOAD = 456. POUNDS

MAXIMUM STRESS = 16531. PSI

MAXIMUM N = 223. IN/IN

22

STRESS (PSI) vs STRAIN (μ in/in)

$E_c=E_t=6.15$ MSI

+ Compression
• Tension

SPECIMEN NUMBER: 1-HICK BEAM #8

DATE OF TEST   : 16 DEC 75

CORE MATERIAL : CPR URETHANE 9)/6-4

CORE DIMENSIONS: 0.760 X 2.620 X 5.120 INCHES

PLY THICKNESS : 0.0185 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN TENSION (μ-IN/IN)	STRAIN COMPRESSION (μ-IN/IN)
6.	214.	0.	0.
26.	946.	145.	145.
52.	1929.	267.	272.
64.	2373.	339.	339.
86.	3129.	455.	459.
108.	3793.	583.	595.
125.	4584.	713.	709.
145.	5275.	841.	836.
165.	6002.	943.	939.
186.	6746.	1075.	1071.
206.	7443.	1193.	1192.
226.	8222.	1301.	1301.
245.	8942.	1437.	1405.
266.	9677.	1533.	1522.
296.	10718.	1643.	1668.
306.	11132.	1764.	1722.
327.	11974.	1817.	1858.
345.	12551.	1995.	1952.
366.	13315.	2123.	2272.
386.	14042.	2205.	2175.
416.	14772.	2354.	2272.
436.	15407.	2471.	2364.
456.	16235.	2581.	2472.
466.	16962.	2690.	2563.
486.	17640.	••••••	•••••••

MAXIMUM LOAD = 486. POUNDS

MAXIMUM STRESS = 17640. PSI

MAXIMUM μ = 727. μΙΝ/ΙΝ

23

$E_c = E_t = 7.33$ MSI

+ Compression
• Tension

STRESS (PSI)

STRAIN (μ in/in)

SPECIMEN NUMBER: 1-HOON BEAM #9

DATE OF TEST : 5 FEB 76

CORE MATERIAL : PVC FOAM

CORE DIMENSIONS: 0.721 X 2.470 X 5.000 INCHES

PLY THICKNESS : 0.0153 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN COMPRESSION (U-IN/IN)	STRAIN TENSION (U-IN/IN)
6.	298.	0.	0.
50.	2479.	410.	410.
106.	5256.	660.	650.
158.	7756.	1050.	1070.
206.	10215.	1330.	1350.
254.	12595.	1640.	1660.
289.	14281.	1890.	1900.
316.	15670.	2060.	2090.
351.	17405.	2280.	2360.
378.	18744.	2490.	2530.
408.	20232.	2660.	2750.
456.	22612.	2980.	2980.
497.	24645.	3200.	3340.
541.	26827.	3760.	3740.
577.	28612.	3880.	3890.
637.	33100.	4070.	4370.
657.	32573.	4400.	4380.
678.	33620.	4500.	4530.
706.	35009.	4730.	4760.
753.	37340.	5090.	5110.
795.	39518.	5430.	5430.
822.	41055.	5610.	5620.
846.	41951.	*********	

MAXIMUM LOAD = 846. POUNDS

MAXIMUM STRESS = 41951. PSI

MAXIMUM N = 642. LB/IN

E_t=7.17 MSI

E_c=6.78 MSI

STRESS
(PSI)

+ Compression
• Tension

30000

20000

10000

2000   4000   6000

STRAIN (μ in/in)

SPECIMEN NUMBER: 1-HOON BEAM #1C

DATE OF TEST   : 5 FEB 76

CORE MATERIAL : PVC FOAM

CORE DIMENSIONS: 0.693 X 2.660 X 5.000 INCHES
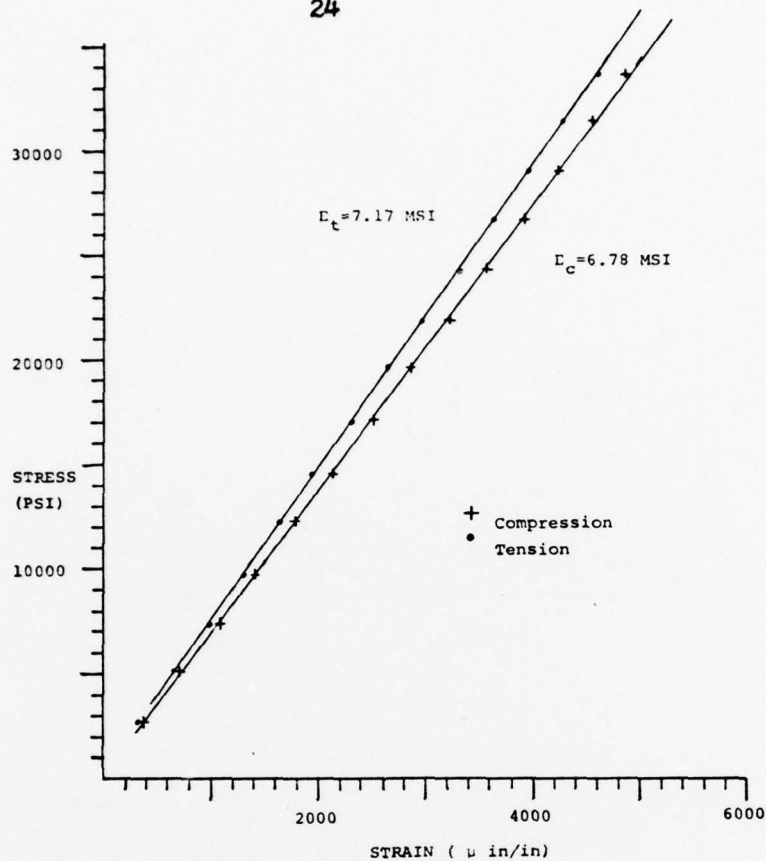
PLY THICKNESS : 0.0153 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN COMPRESSION (u-IN/IN)	STRAIN TENSION (u-IN/IN)
6.	287.	0.	0.
58.	2776.	380.	340.
106.	5074.	730.	670.
156.	7467.	1100.	1000.
204.	9765.	1420.	1310.
258.	12349.	1800.	1640.
305.	14599.	2150.	1970.
357.	17089.	2510.	2310.
408.	19529.	2880.	2660.
458.	21922.	3240.	2990.
528.	24316.	3590.	3330.
554.	26709.	3910.	3640.
606.	29006.	4250.	3980.
658.	31495.	4570.	4300.
704.	33607.	4930.	4620.
756.	36166.	●●●●●●●●●●●●●●●●●●●●●●●●●●●●●●●●●●●●●

MAXIMUM LOAD = 756. POUNDS

MAXIMUM STRESS = 36166. PSI

MAXIMUM   =   554. LB/IN

E_c=7.66 MSI

E_t=7.63 MSI

STRESS (PSI)

30000

20000

10000

+ Tension
• Compression

2000   4000

STRAIN (u in/in)

SPECIMEN NUMBER: 1-HCOV BEAM #11

DATE OF TEST : 5 FEB 76

CCRE MATERIAL : PVC FOAM

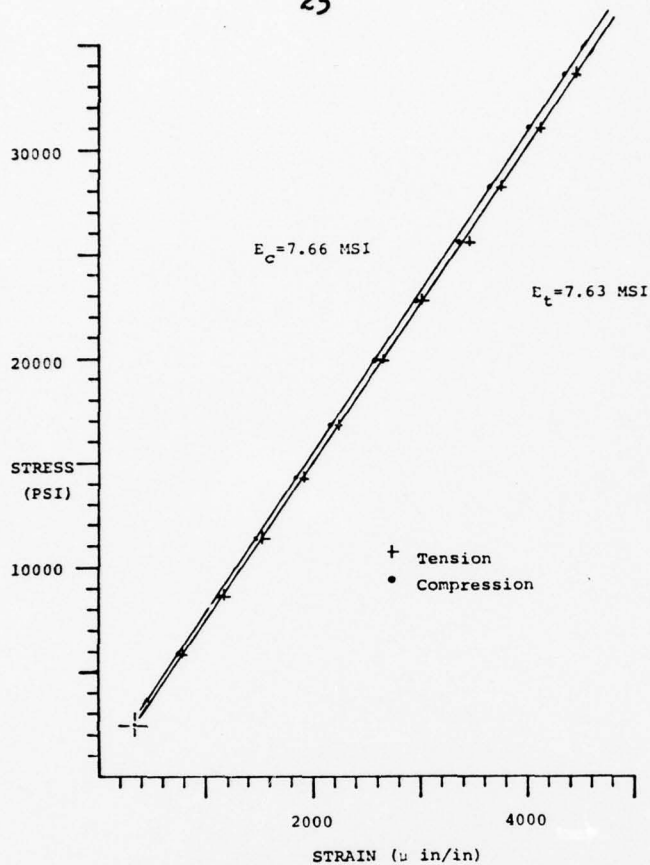CCRE DIMENSIONS: 0.632 X 2.490 X 5.000 INCHES

PLY THICKNESS : 0.0143 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN COMPRESSION (U-IN/IN)	STRAIN TENSION (U-IN/IN)
6.	334.	0.	0.
45.	2504.	350.	350.
106.	5899.	780.	790.
156.	8682.	1120.	1190.
206.	11464.	1480.	1540.
258.	14358.	1830.	1930.
304.	16918.	2180.	2260.
359.	19979.	2590.	2670.
409.	22762.	2950.	3030.
459.	25545.	3370.	3490.
508.	28272.	3670.	3780.
557.	30999.	4020.	4150.
607.	33781.	4570.	4490.
637.	35451.		

MAXIMUM LOAD = 637. POUNDS

MAXIMUM STRESS = 35451. PSI

MAXIMUM N = 537. Le/IN

E_c=7.35 MSI

E_t=7.14 MSI

+ Tension

• Compression

STRESS (PSI)

STRAIN (μ in/in)

SPECIMEN NUMBER: 1-HOON BEAM #12

DATE OF TEST : 5 FEB 76

CORE MATERIAL : PVC FOAM

CORE DIMENSIONS: 0.730 X 2.400 X 5.000 INCHES

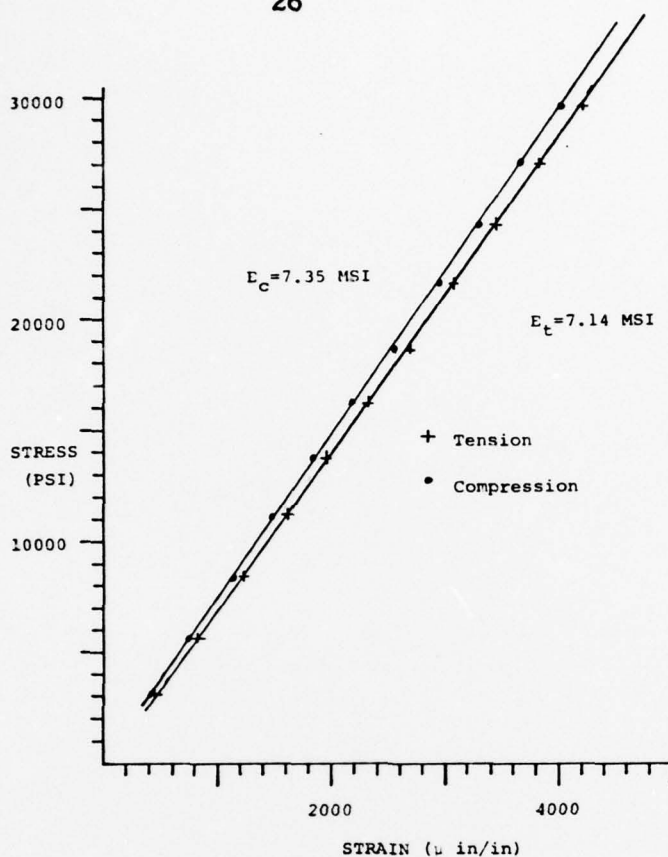PLY THICKNESS : 0.0145 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN COMPRESSION (U-IN/IN)	STRAIN TENSION (U-IN/IN)
6.	320.	0.	0.
58.	3089.	410.	450.
106.	5645.	760.	930.
158.	8415.	1140.	1230.
209.	11131.	1490.	1610.
258.	13740.	1840.	1980.
306.	16297.	2190.	2340.
354.	18853.	2560.	2700.
407.	21676.	2940.	3090.
457.	24339.	3300.	3460.
509.	27055.	3670.	3850.
557.	29664.	4020.	4210.
591.	31475.*************************************		

MAXIMUM LOAD = 591. POUNDS

MAXIMUM STRESS = 31475. PSI

MAXIMUM N = 450. LB/IN

E_t=8.16 MSI

E_c=7.55 MSI

STRESS (PSI)

30000

20000

10000

+ Tension

• Compression

2000   4000

STRAIN (u in/in)

SPECIMEN NUMBER: 1-MOON BEAM # 13

DATE OF TEST   : 5 FEB 76

CORE MATERIAL : PVC FOAM

CORE DIMENSIONS: 0.692 X 2.650 X 5.000 INCHES
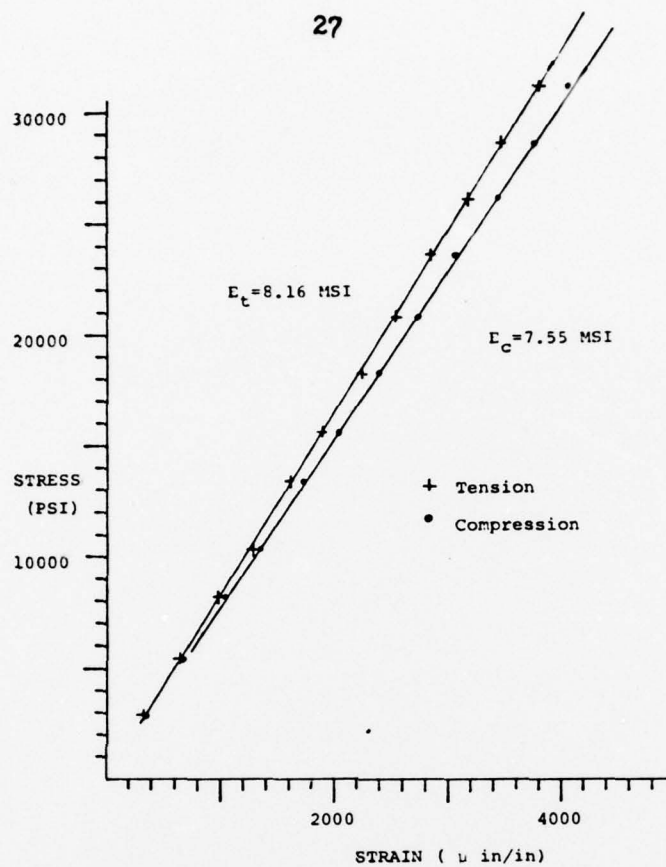
PLY THICKNESS : 0.0143 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN COMPRESSION (U-IN/IN)	STRAIN TENSION (U-IN/IN)
6.	309.	0.	0.
53.	2990.	300.	340.
106.	5465.	690.	650.
160.	8248.	1040.	990.
208.	10723.	1370.	1290.
261.	13455.	1720.	1610.
305.	15723.	2040.	1900.
356.	18353.	2400.	2240.
404.	20827.	2720.	2540.
457.	23555.	3070.	2860.
508.	26185.	3430.	3190.
557.	28715.	3780.	3490.
608.	31344.	4070.	3800.
636.	32747. ∘∗∘∗∗∘∘∘∘∘∘∘∗∗∘∘∘∗∘∗∗∗∘∘∗∗∗∘∘∗∘		

MAXIMUM LOAD = 636. POUNDS

MAXIMUM STRESS =   32747. PSI

MAXIMUM G =   469. LB/IN

$E_c = E_t = 7.60$ MSI

STRESS (PSI)

+ Tension
• Compression

STRAIN (μ in/in)

SPECIMEN NUMBER: 1-HCON BEAM # 14

DATE OF TEST   : 5 FEB 76

CORE MATERIAL : PVC FOAM
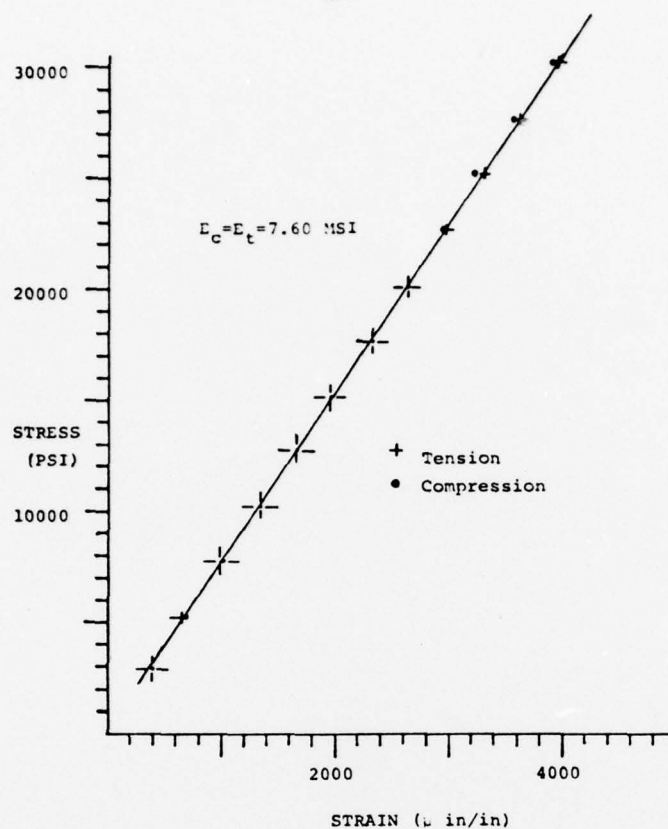
CORE DIMENSIONS: 0.715 X 2.650 X 5.000 INCHES
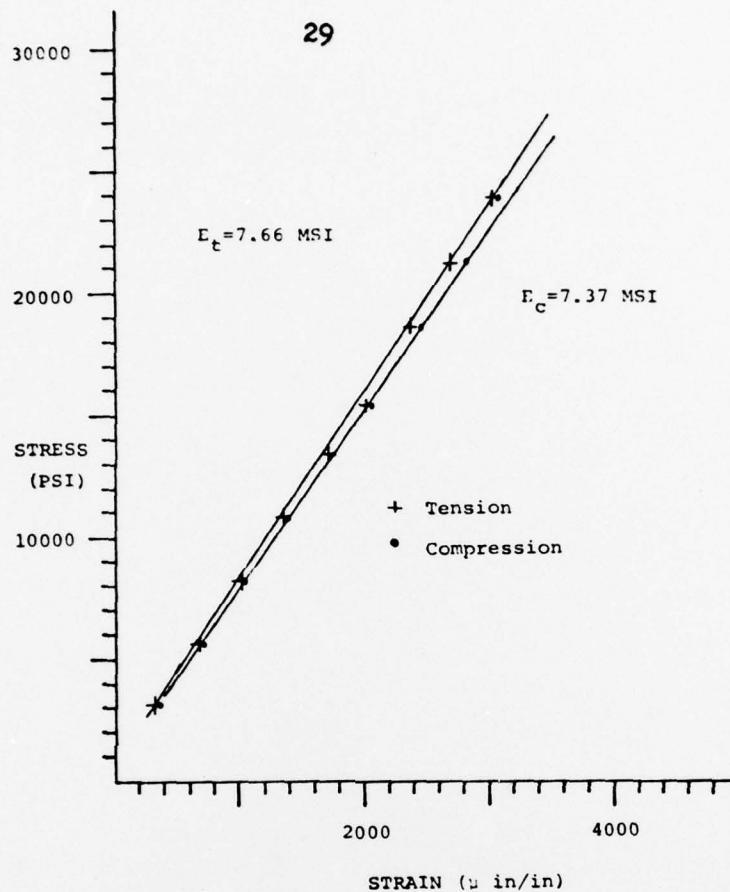
PLY THICKNESS : 0.0144 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN COMPRESSION (U-IN/IN)	STRAIN TENSION (U-IN/IN)
6.	297.	0.	0.
60.	2974.	400.	400.
106.	5255.	700.	690.
157.	7783.	1040.	1030.
206.	10212.	1350.	1350.
258.	12740.	1690.	1630.
304.	15070.	1900.	1980.
357.	17696.	2330.	2330.
406.	20127.	2640.	2640.
456.	22606.	2950.	2900.
508.	25185.	3260.	3310.
558.	27662.	3590.	3620.
613.	30240.	3910.	3940.
646.	32025.	••••••••••••••••••••••••••••••••	

MAXIMUM LOAD = 646. POUNDS

MAXIMUM STRESS =   32025. PSI

MAXIMUM N =   461. LB/IN

E_t=7.66 MSI

E_c=7.37 MSI

STRESS (PSI)

30000

20000

10000

+ Tension

● Compression

2000   4000

STRAIN (µ in/in)

SPECIMEN NUMBER: 1-HOON BEAM #15

DATE OF TEST   : 12 FEB 76

CORE MATERIAL : PVC FOAM

CORE DIMENSIONS: 0.710 X 2.640 X 5.000 INCHES

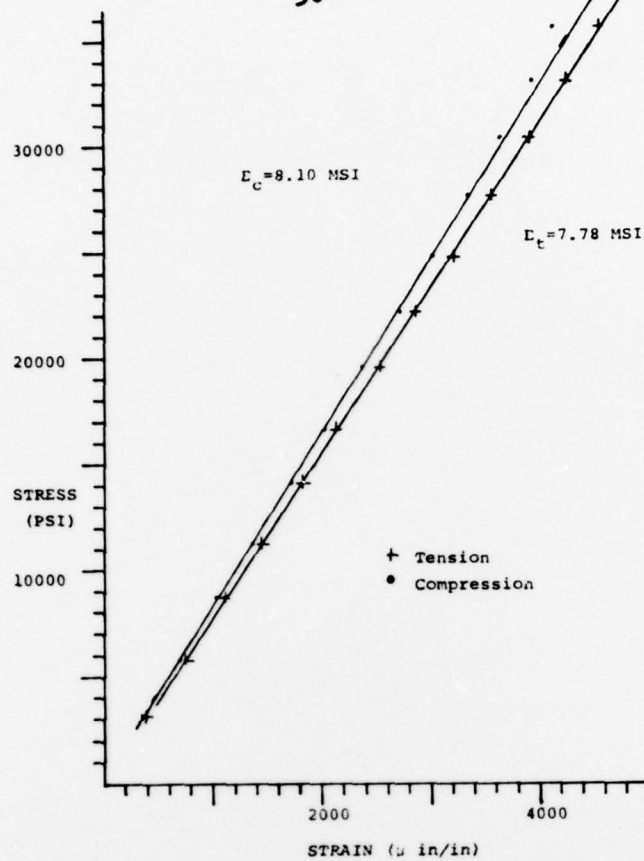PLY THICKNESS : 0.0138 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN COMPRESSION (U-IN/IN)	STRAIN TENSION (U-IN/IN)
6.	314.	0.	0.
53.	3035.	360.	340.
106.	5547.	710.	700.
157.	8215.	1060.	1050.
207.	10832.	1400.	1360.
257.	13448.	1740.	1700.
305.	15960.	2070.	2010.
357.	18681.	2470.	2380.
409.	21349.	2810.	2700.
457.	23913.	3090.	3340.
507.	26550.	************************************	

MAXIMUM LOAD = 507. POUNDS

MAXIMUM STRESS = 26550. PSI

MAXIMUM N = 366. LB/IN

Graph: STRESS (PSI) vs STRAIN (u in/in)

E_c=8.10 MSI

E_t=7.78 MSI

+ Tension
• Compression

SPECIMEN NUMBER: 1-HOUR BEAM # 1C

DATE OF TEST : 12 FEB 76

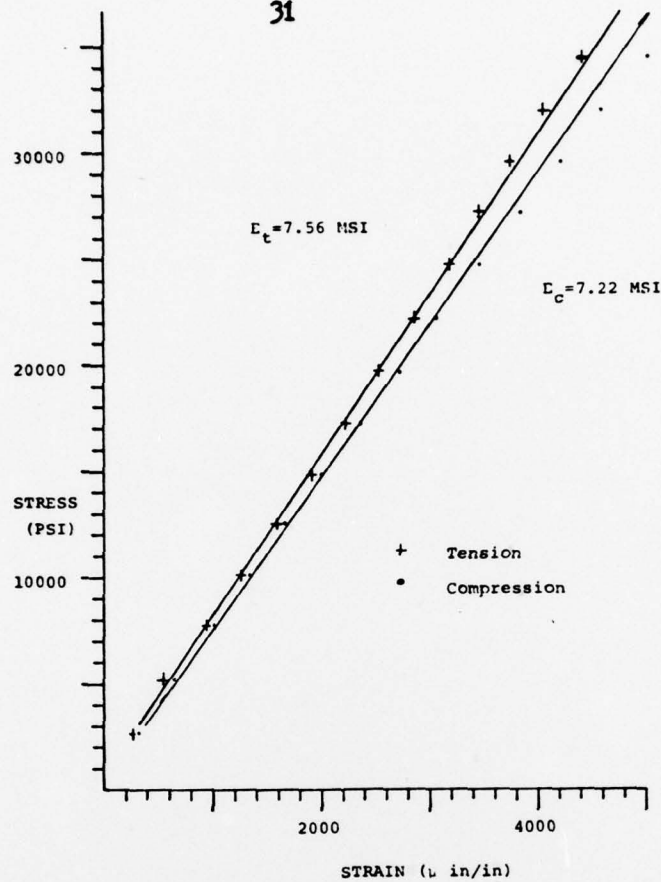CORE MATERIAL : PVC FOAM

CORE DIMENSIONS: 0.669 X 2.640 X 5.000 INCHES

PLY THICKNESS : 0.0140 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN COMPRESSION (U-IN/IN)	STRAIN TENSION (U-IN/IN)
6.	328.	0.	0.
58.	3170.	360.	390.
106.	5794.	700.	750.
160.	8746.	1040.	1110.
207.	11315.	1380.	1460.
258.	14102.	1710.	1820.
304.	16616.	2020.	2150.
358.	19568.	2390.	2550.
409.	22301.	2710.	2890.
456.	24925.	3010.	3220.
507.	27712.	3350.	3590.
558.	30500.	3650.	3940.
608.	33233.	3930.	4290.
654.	35747.	4130.	4550.
676.	36950.**************************************		

MAXIMUM LOAD = 676. POUNDS

MAXIMUM STRESS = 36950. PSI

MAXIMUM N = 517. LB/IN

E_t=7.56 MSI

E_c=7.22 MSI

STRESS
(PSI)

+   Tension

•   Compression

STRAIN (μ in/in)

SPECIMEN NUMBER: I-HCON BEAM # 17

DATE OF TEST   : 12 FEB 76

CORE MATERIAL   : PVC FOAM
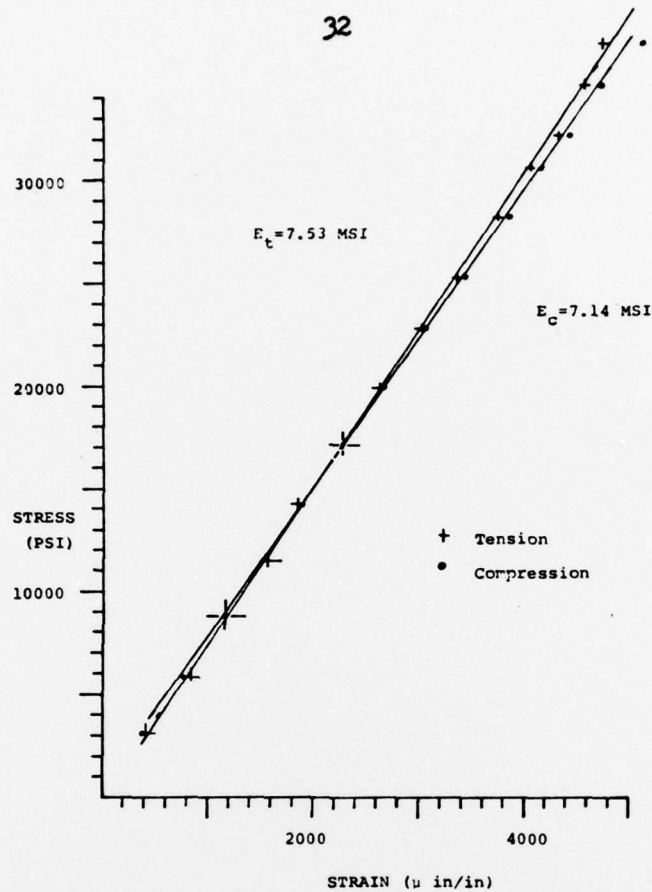
CORE DIMENSIONS: 0.714 X 2.680 X 5.000 INCHES

PLY THICKNESS   : 0.0145 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN COMPRESSION (U-IN/IN)	STRAIN TENSION (U-IN/IN)
6.	292.	0.	0.
55.	2661.	310.	280.
106.	5106.	660.	655.
158.	7701.	1010.	970.
207.	10089.	1350.	1290.
258.	12575.	1680.	1600.
305.	14866.	2020.	1925.
356.	17352.	2380.	2240.
402.	19594.	2720.	2540.
456.	22226.	3080.	2860.
506.	24760.	3420.	3200.
557.	27146.	3830.	3480.
607.	29585.	4210.	3790.
657.	32023.	4600.	4090.
708.	34508.	5030.	4410.
726.	35386.••		

MAXIMUM LOAD = 726. POUNDS

MAXIMUM STRESS =   35386. PSI

MAXIMUM N =   513. LB/IN

E_t=7.53 MSI

E_c=7.14 MSI

30000

STRESS
(PSI)

20000

10000

+ Tension

• Compression

2000   4000

STRAIN (µ in/in)

SPECIMEN NUMBER: I-HOON BEAM # 18

DATE OF TEST   : 12 FEB 76

CORE MATERIAL : PVC FOAM

CORE DIMENSIONS: 0.705 X 2.490 X 5.000 INCHES

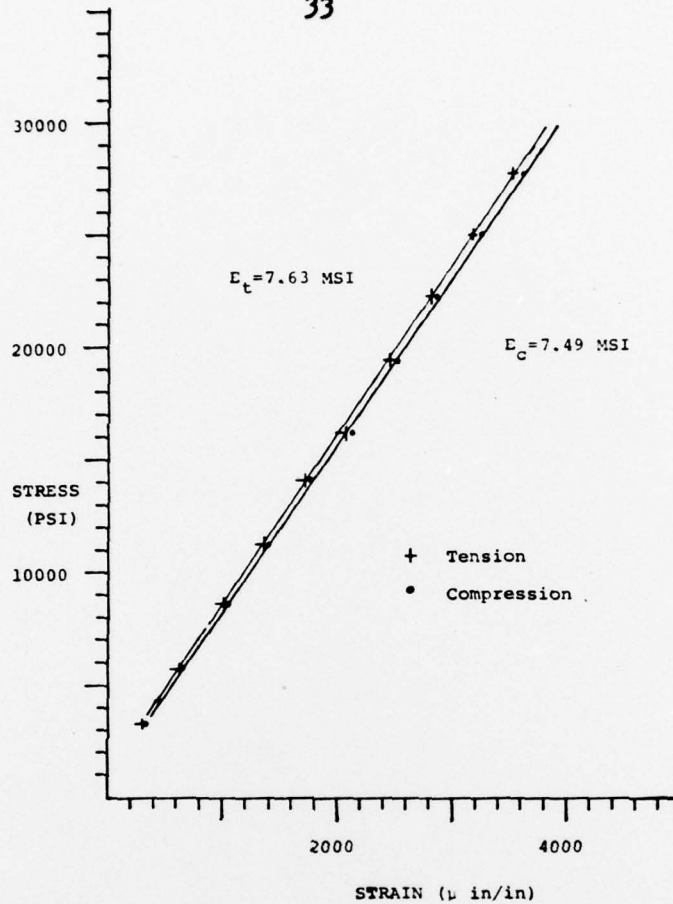PLY THICKNESS : 0.0138 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN COMPRESSION (U-IN/IN)	STRAIN TENSION (U-IN/IN)
6.	335.	0.	0.
56.	3126.	350.	430.
106.	5922.	760.	840.
159.	8883.	1160.	1180.
207.	11564.	1540.	1570.
256.	14301.	1900.	1980.
307.	17151.	2300.	2300.
356.	19898.	2680.	2650.
409.	22844.	3050.	3050.
454.	25363.	3440.	3380.
508.	28268.	3850.	3780.
548.	30614.	4190.	4080.
579.	32346.	4460.	4340.
620.	34636.	4760.	4600.
656.	36647.	5170.	4770.
662.	36993.	**************************************

MAXIMUM LOAD = 662. POUNDS

MAXIMUM STRESS = 36993. PSI

MAXIMUM % =   513. UE/IN

E_t=7.63 MSI

E_c=7.49 MSI

STRESS (PSI)

30000

20000

10000

+ Tension

• Compression

2000   4000

STRAIN (μ in/in)

SPECIMEN NUMBER: 1-HOON BEAM # 19

DATE OF TEST   : 12 FEB 76

CORE MATERIAL   : PVC FOAM
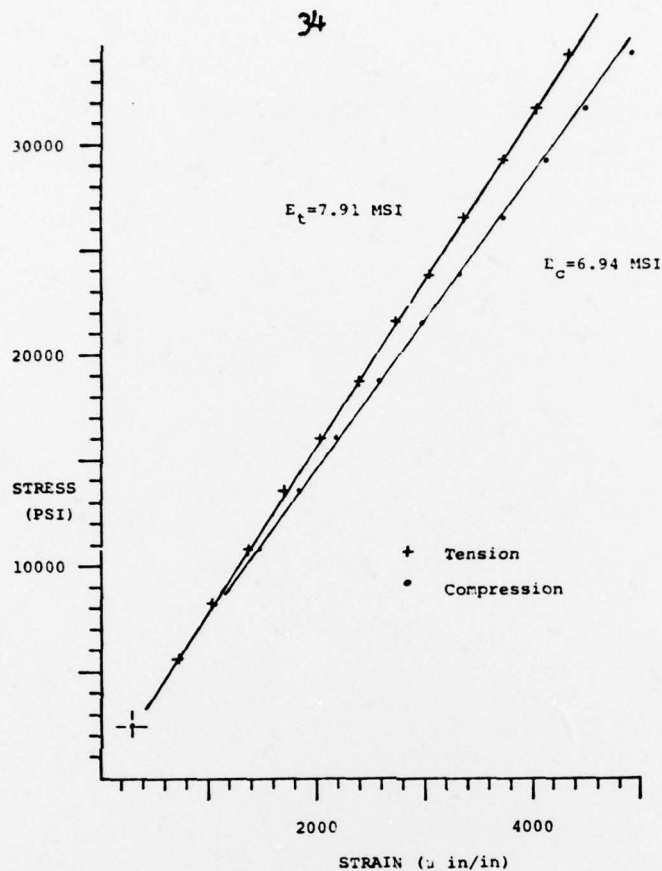
CORE DIMENSIONS: 0.704 X 2.570 X 5.000 INCHES

PLY THICKNESS   : 0.0136 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN COMPRESSION (U-IN/IN)	STRAIN TENSION (U-IN/IN)
6.	330.	0.	0.
61.	3356.	920.	310.
106.	5831.	560.	650.
157.	8657.	1040.	1030.
237.	11388.	1400.	1370.
256.	14084.	1770.	1730.
304.	16724.	2120.	2060.
354.	19475.	2530.	2450.
407.	22391.	2890.	2820.
456.	25086.	3280.	3190.
506.	27837.	3610.	3510.
560.	30900.*************************************		

MAXIMUM LOAD = 560. POUNDS

MAXIMUM STRESS =   30900. PSI

MAXIMUM N =   419. LB/IN

E_t=7.91 MSI

E_c=6.94 MSI

STRESS
(PSI)

+   Tension

•   Compression

STRAIN (u in/in)

SPECIMEN NUMBER: 1-MOON BEAM • 2C

DATE OF TEST   : 12 FEB 76

CORE MATERIAL   : PVC FOAM

CORE DIMENSIONS: 0.705 X 2.570 X 5.000 INCHES

PLY THICKNESS   : 0.0142 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN COMPRESSION (U-IN/IN)	STRAIN TENSION (U-IN/IN)
6.	315.	0.	0.
48.	2523.	300.	300.
108.	5678.	760.	710.
157.	8254.	1090.	1040.
208.	10935.	1470.	1370.
258.	13564.	1810.	1700.
305.	16034.	2190.	2030.
355.	18621.	2590.	2400.
410.	21554.	2990.	2740.
456.	23973.	3320.	3040.
506.	26601.	3720.	3360.
559.	29386.	4120.	3720.
606.	31852.	4500.	4030.
656.	34487.	4920.	4350.
696.	36540.	**********************************	

MAXIMUM LOAD = 696. POUNDS

MAXIMUM STRESS = 36540. PSI

MAXIMUM N = 520. LB/IN.

APPENDIX A

TABLE A1   FOAM PROPERTIES

FOAM		CPR URETHANE 9006-4	AIREX 01/18 PVC FOAM
COMPRESSIVE STRENGTH (psi)	PARALLEL *	55	120
	PERPENDICULAR	75	
COMPRESSIVE MODULUS OF ELASTICITY (psi)	PARALLEL	900	5000
	PERPENDICULAR	2000	
TENSILE STRENGTH (psi)	PARALLEL	70	260
	PERPENDICULAR	90	
SHEAR STRENGTH (psi)		50	125
NOMINAL DENSITY (lb/ft^3)		4	6

* Indicates a direction of loading parallel to the face of the beam and applies only to the urethane foam.
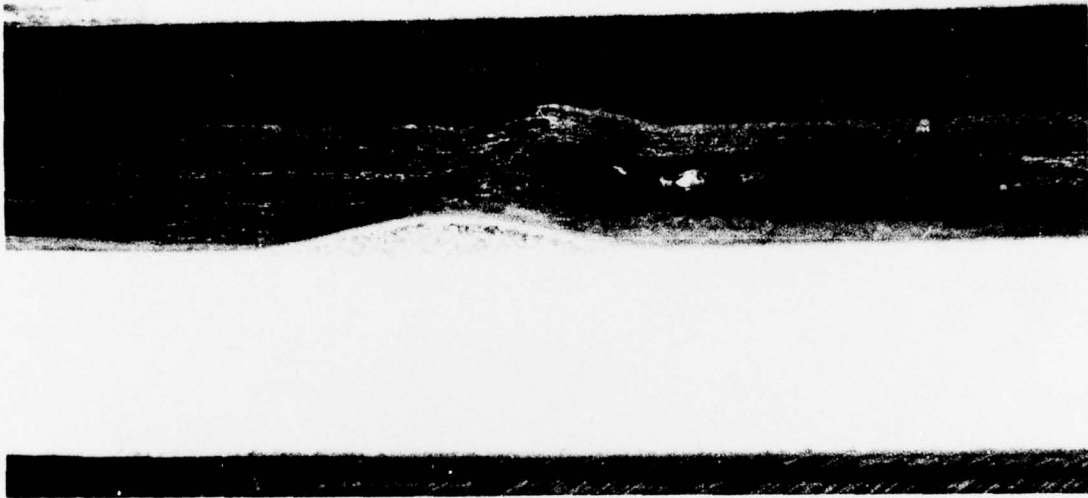
TABLE A2   GRAPHITE PROPERTIES

MANUFACTURER	Hercules Incorporated
PHYSICAL PROPERTIES* Fiber Volume Density Ply Thickness	 59% .0577 lb/in^3 .0053 in.
LAMINATE MECHANICAL PROPERTIES* 0° Tensile Strength 0° Tensile Modulus 0° Flex Strength 0° Flex Modulus Short Beam Shear Test	 239 ksi 20.5 msi 276 ksi 17.2 msi 18.9 ksi
* Values are for 1-ply laminate cured as recommended by the manufacturer.	

Manufacturer's Recommended
Graphite Curing Cycle A01

Laminates shall be cured as follows:

a. Preheat press platens to $275 \pm 5^{\circ}F$.

b. Place mold in press and apply contact pressure of 10-15 pounds per square inch (psi).

c. Hold at contact pressure of Step b. for 18 ± 1 minutes.

d. Increase pressure to $100 + 10, - 0$ psi.

e. Increase temperature to $300 \pm 5^{\circ}F$.

f. Hold at $100 + 10, - 0$ psi and $300 \pm 5^{\circ}F$ for 30 ± 5 minutes.

g. Increase temperature to $350 \pm 5^{\circ}F$ and hold for 30 ± 5 minutes.

h. Decrease temperature at a rate of $13 \pm 2^{\circ}F$ per minute until temperature of $150 \pm 5^{\circ}F$ is reached.

i. Release pressure.

j. Remove mold from press.

k. Remove laminate from mold.

APPENDIX B

Failure Mode "a"

Failure Mode "a" was a tension failure of the foam core which allowed the graphite facing to buckle outward. It was found to occur only with the Urethane foam core beams and was the method of failure in all eight cases. The half-wavelength of the buckling varied from 5/8" to 1-3/8" and often varied from one edge of the beam to the other. Failure was very rapid and was always occumpanied by a "popping" sound as the graphite tore loose. The failures occurred at relatively low levels of stress when compared with the PVC foam core beams.

Failure Mode "b"

Failure Mode "b" was a compression failure of the graphite facing.
This failure mode occurred on five of twelve occasions where PVC
foam was used as core material. The failure line was characteris-
tically very jagged through the facing with little apparent permanent
deformation of the core material. Failures occurred at stress levels
of 25,000-35,000 psi. (The compressive ultimate strength of the
laminate is about 90,000 psi.)

Failure Mode "c"

Failure Mode "c" appeared to be a combination failure of the PVC

foam and the graphite facing although it is probable that one caused

the other to occur. The failure of the foam was a compression

failure and can be identified on the beam by the straight, sharp

V-shaped indentation. It varied in length from about $\frac{1}{2}$" to 1-3/4"

with the remainder of the facing failing in compression similarly to

Mode "b". This mode of failure occurred on six of twelve occasions

with the PVC foam core beams.

Failure Mode "d"

Failure Mode "d" was one-of-a-kind and occurred only on beam
#17. It is very similar to Mode "b" except that some inter-
laminar delamination occurred on one edge of the beam sufficient
to weaken the beam locally and allow compressive failure of
the graphite facing to occur at that site. Although delamination
was about $\frac{1}{4}$" wide, it is interesting to note that the maximum
compressive load, N_{max}, was comparable to that of all other failures.